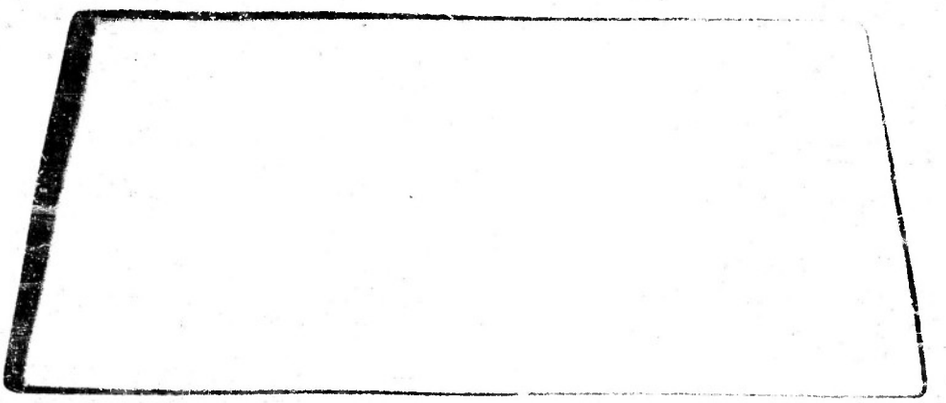

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Liberation of Electrons by Fast Neutral Helium Atoms from a Tungsten Surface

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SYNOPSIS

The electron emission from tungsten by bombarding helium atoms of energy ranging from 300 to 3500 ev has been measured for a surface with less than a monolayer and with multilayer adsorbed gas. The yield expressed in electrons per particle rises almost linearly from ~ 0 at 300 ev to .42 el /particle at 3500 ev for 1500°K (< monolayer of O) target. Further adsorption of gas (cold target) gives a much increased yield. These yields are compared with the ion under like conditions. For low energies the ion yield is .16 el/particle larger than the neutral atom. This remains almost constant for a hot target with increasing energy of the particles. The normal velocity and a tangential component velocity distributions are compared for the ion and neutral atom on hot and cold targets. The similarities and differences are discussed and a mechanism of the ionization by collision of the adsorbed gas and bombarding atoms is suggested to explain some of the behavior.

INTRODUCTION

Under bombardment by ions or neutral atoms of sufficient energy, electrons are liberated from a metal surface. For the ion two mechanisms are possible which are distinct in terms of the source of the energy. These are 1) a potential ejection which is dependent upon the energy of ionization or excitation of the approaching particle and 2) kinetic ejection wherein the source of energy for liberation is the kinetic energy of the particle. For a neutral atom in the ground state, of course, kinetic ejection alone occurs. This particular phenomenon is the object of the investigation reported here.

A mechanism for the potential electron emission by an ion, that was suggested by Oliphant and Moon[1] and that was developed by Massey,[2] and Cobas and Lamb,[3] envisions first the capture of a metallic electron by a resonance process into an excited state of the approaching ion (figure 1a). Since Oliphant apparently observed reflected metastable helium atoms on bombarding molybdenum by helium ions, it was thought that neutralization to the metastable state was essential to the process. A subsequent capture of an electron into the ground state then occurred with the ejection of the metastable state electron as the observed "secondary" electron. Energy limitations on the process imposed by the position of the excited level and the Fermi level of the metal are met if the image force and repulsive force potential energies are neglected. Varnerin[4] has since shown the impossibility of this method of neutralization from an energy standpoint for helium on molybdenum when the image force is included.

An alternative mechanism suggested by Shekhter[5] involves the direct neutralization to the ground state with the energy of this capture given to another metallic electron which if it escapes the metal is the observed "secondary" electron. (figure 1b). Recent work by Hagstrum[6] on electron ejection from molybdenum and tungsten by slow rare gas ions indicates that this second mechanism predominates in the emission.

A process for kinetic liberation proposed by Kapitza[7] is a localized thermionic emission. A bombarding particle releases a part of its kinetic energy to a small volume of the metal lattice and in doing so produces for a short time an extremely high effective temperature. A thermionic emission of electrons results such that the velocity distribution of the electrons is characteristic of thermionic emission at this temperature. Evidence appearing to support this[1,8] arises in the measurement by the retarding field method of the energy distribution of the electrons. The usual semi-logarithmic plot has given approximately a straight line with a slope characteristic of temperatures of 20,000° to 50,000°K. It seems now, however, that the semi-logarithmic plot is misleading in this interpretation. Cathode sputtering theories have developed along a line similar to this. And Townes[9] has shown that high temperatures over limited volumes with diameters of several Angstroms are quite possible under low energy ion bombardment. Yet it is not evident how an equilibrium electron velocity distribution characteristic of the temperature of this small region could be acquired by electrons which have mean free paths several hundred times larger than the region.

Experiments by Walcher[10] and associates indicate the importance of electronegative adsorbed gases in kinetic liberation. The adsorption of these gases increased the emission while electropositive gases decreased it. Ploch[10] found the yield for various alkali ions to be primarily velocity dependent. They conclude the process to be a liberation of electrons bound to the adsorbed gas atoms by the bombardment of the incident ions.

There exists, however, some confusion over the relative contributions of the potential and kinetic processes for a fast ion, say several kev. Not only does the adsorption of gas affect the efficiency of the potential liberation[6,11], but also seems to increase the kinetic yield. Furthermore, the efficiency of the potential process would be expected to exhibit a velocity dependence, with this, then, superimposed on the increasing kinetic yield.

The present study was undertaken for the purpose of investigating further the characteristics of the kinetic liberation produced by fast neutral helium atoms in the ground state and comparing these with the emission by ions under like conditions. Such properties as the fraction of ions reflected, the electron yield for ions and neutral atoms on a hot and a gas covered tungsten surface, the normal and tangential component velocity distributions of the emitted electrons and the angular distribution of the reflected particles have been measured.

APPARATUS

The apparatus used in all of the following experiments consisted of the same ion gun, neutralizing chamber, shutters, etc., but with different electrode arrangements in the target region - each suited to the particular measurement. Figure 2 shows a schematic diagram of the apparatus with the target arrangement for ion reflection measurements. The vacuum system was a combination metal and glass demountable type with the gun and target region separately pumped and trapped. The residual pressure before admission of helium was in the neighborhood of 7×10^{-7} mm Hg.

Electrons, emitted from a tungsten filament, are accelerated by a 75 volt potential difference, which is the onset potential by He^{++} ionization. This electron flux ionizes the helium gas admitted to the field-free region I. On occasions a small axial magnetic field is used to increase the ionization. Next, acceleration of these ions to the desired energy forms the ion beam, part of which is neutralized by charge exchange with helium gas atoms in region II. Since only low angle neutralizing collisions contribute to the neutral atom beam, the energy of the particles is essentially that of the ions. A reversed potential difference applied on grid (G) is used to remove ions when a neutral atom beam only is desired. A mechanical shutter (S) permits complete stopping of the beam. The apertures are such that the diameter of the beam on reaching the target is about 1 mm.

REFLECTION OF IONS

In most experiments on electron emission under fast ion bombardment there is observed, when the target is sufficiently positive to hold electrons liberated from it, a positive current to the collector. This current may represent ions reflected from the target and/or electrons liberated from the collector by impinging ions, metastable or ground state neutral atoms. Since this collector current is observed under neutral atom bombardment of the target, some reflected particles have sufficient energy to eject electrons by the kinetic process. This is certainly true also under ion bombardment so that some selective arrangement is necessary to observe the true reflected ion current.

For this purpose, a negative grid was placed before the collector to suppress the electron emission. To do this without contributing an electron emission sufficient to mask a small ion current, the grid must present the least possible obstruction commensurate with a continuous equipotential surface sufficiently negative to prevent electron escape from the collector. An electrolytic tank investigation led to a grid of 0.005 in. wires, 3/32 inch apart for which the most negative, continuous equipotential surface was known for given electrode potentials. An axial magnetic field of several hundred gauss was available to prevent the flow of electrons from the target to the collector. The target was a 0.001 in. tungsten ribbon mounted flush with the brass plate and heated during observations to about 1300°K.

With the target sufficiently positive to hold electrons and negative ions, a small negative current to the collector was always observed under bombardment by either ions or neutral atoms of 500 to 2000 ev. energy. This is interpreted as an electron current produced by bombardment of the grid wires by the reflected particles. An attempt to evaluate a reflected ion current from differences under bombardment by ions and neutral atoms did not prove successful. Such an analysis indicates either no reflected ion current or proportionately equal amounts for incident ions and neutral atoms. An upper limit in the ion reflection may be deduced, however, from the geometry of the grid wire obstruction and from the measured values of the electron emission from the collector induced by the reflected particles. For helium ions with energies from 500 - 2000 ev incident at 30°with the normal on tungsten at 1300°K, the fraction reflected is less than 0.1% of the incident beam. Helium ions on Pt, Ta, Rh also show less than 0.1% reflected.

MEASUREMENT OF THE ELECTRON YIELD FOR IONS AND NEUTRAL ATOMS

1) Apparatus

For the measurement of the number of electrons released per incident particle (γ) and the velocity distributions of the emitted electrons, a target and collector arrangement as shown in figure 3 was used. The target was a tungsten strip 0.001 x 1/8 x 1/4 in. and was mounted flush with a brass plate 3 x 3 7/8 in. One centimeter from this and parallel to it was a similiar brass plate to serve as the collector. This plate has a center section containing a Faraday cage mounted behind a slit such that the assembly could be moved parallel to the plane of the collector plate. This movable collector was used in subsequent experiments on the tangential component velocity distribution. The entire assembly was tilted at 30° to the beam direction so that emission normal to the target could be observed.

2) Neutral Atom Equivalent Current

The determination of γ for the positive ions requires simply the measurement of the electron emission from the target when about 30 · negative and the total current to both collector and target. The ratio is the quantity γ' . For neutral atoms the size of the equivalent current must be obtained by indirect means. One method for doing this requires the measurement of the slow ion current in the neutralizing chamber. Since this charge exchange process is a resonant one, most of the charge exchange collisions are glancing, thus leaving slow knock-on ions. (Massey and Burhap [11]). This is verified by the relatively low

voltage saturation of the ion current collected in a region in which charge exchange has occurred. Experiments previously done here have shown, though, this method of determining the neutral atom beam to be geometry sensitive. Further, because of the long paths in this apparatus, neutralizations may occur elsewhere especially just outside the apertures of the neutralizing chamber. This coupled with loss of particles through succeeding apertures did not indicate this method to be sufficiently accurate.

The essentially complete neutralization of the incident ions on the target suggests a way of determining the neutral atom beam at the target. Calculations made by Massey, Cobas and Lamb, and Shekhter indicate the neutralization of the ion to occur before actual "contact" with the surface. That is before large repulsive forces are brought into play. If this is so, then the scattering collision of the neutralized ions and the surface would be the same as for an incident neutral atoms. Thus ions and neutral atoms of like energy would be reflected with like energy distributions and so produce proportionate electron emissions from the collector. This assumes, of course, that the ions are reflected in the ground state.

For brevity, let λ = ratio of electron current liberated from the collector by reflected particles when ions only are incident on the target to the electron current liberated from the collector when neutral atoms only are incident on the target. This ratio will have a definte pressure and ion energy dependence

regardless of the what losses occur as the beam passes through the apertures. This may be calculated with knowledge of the cross-section for neutralization. (See Appendix) Because the neutralizing path is not accurately known and the pressure is not measured in this region, values of λ were calculated to match the experimental value at one energy, 1000 ev. Experimental values of the cross-section for neutralization differ widely.[11] Theoretical values calculated by Massey and Smith[12], Dellaporta and Bonfiglioli[13], and Jackson[14] are closer in agreement with each other and with the best experimental values by Hasted[15]. Both the Massey-Smith and Dellaporta-Bonfiglioli and Jackson computed values have been used to calculate λ for ion energies from 300 - 3500 ev for a particular value of λ_{1000}. These are shown in figure 4 along with one set of experimental values. Similar agreement was obtained with other experimental sets for different helium pressures in the neutralizing region corresponding to values of λ_{1000} from 1.33 to 2.42. Both hot and cold targets were used and while the value of the electron emission from the collector are 5 - 10% less for the cold target, the ratio λ was unchanged within the experimental error. Agreement over extended periods of time was within 5%. The experimental values seem to fit the MSDB theoretical cross-sections better than those of Jackson except below 1000 ev where these results indicate the MSDB cross-section rises too steeply with decreasing energy. This agreement tends to support, however, the assumptions made on the reflection of the particles.

3) Surface Adsorbed Gas

It is evident from the ultimate pressure obtainable in this apparatus that no useable length of time would exist after flashing the target during which the target would be gas free. An estimated adsorption rate would indicate less than 1 sec. for the formation of a monolayer assuming adsorbed atoms with a long "sitting time". Hagstrum[6], working with excellent vacuum conditions which allowed extended observations to be made on a gas free surface, found a reduction of 20% in γ_i for He^+ on Mo with adsorption of a monolayer. Similar behavior is noted by Parker[16] and Varney[17]. Dependence of the yield on the adsorbed gas is to be expected.

For some time through work done principally by Arnot et al[18], it has been known that positive ions bombarding a surface will remove negative ions of the species of the adsorbed gas. It has been found in the present work that neutral atoms are equally effective. This negative ion yield is small even for a gas covered surface. For example, it is only a few percent of the electron yield for 1000 ev He^+ on gas covered tungsten. This technique has been used to investigate the extent of the electronegative adsorbed gas on the target as a function of the temperature.

As in Figure 3, an axial magnetic field prevented electrons from reaching the slit collector set opposite the target. The negative ion current observed with the target 30 v negative is shown in figure 5 as a function of the target temperature. No major differences were observed between increasing and decreasing temperatures as long as sufficient time to acquire equilibrium

elapsed between temperature changes. It is apparent from this alone that adsorbed atoms are present to temperatures well above those possible for target operation during measurements on electron ejection. A temperature of 1500°K represents the upper limit whereat thermionic emission fluctuations mask the ion or neutral atom induced emission.

It is interesting to compare this with Van Cleave's[19] measurement of the accomodation coefficient of neon on tungsten exposed to oxygen, again as a function of the temperature of the wire. This is shown also in figure 5. Both curves indicate a constant amount of adsorbed gas (chemisorbed oxygen) in the region from about 1000°K to 1700°K with a decrease thereafter. Below 1000°K additional layers of gas are adsorbed and in the present experiment this will consist of other residual gases as well as oxygen at the lower temperatures. The large temperature region in which the amount of adsorbed gas is constant obviates the necessity of careful temperature control for the same surface conditions.

Measurements by Roberts and others[20] indicate the first layer of oxygen adsorbed on tungsten to have a heat of adsorption above 100 kilocal/mol. This is not completely removed until 2200°K and represents the layer present from 1000°K to 1700°K. This chemisorbed layer is supposed to consist of an atomic film with 8% of the sites vacant[21]. At lower temperatures the 8% gaps are filled with oxygen molecules and a second less atable film is adsorbed on top of this. For all measurements labeled hot target, the temperature was between 1300°K and 1500°K in the region of a single adsorbed layer.

4) Results and Discussion of the Electron Yield

Since the beam consists of a mixture of ions and neutral atoms both electron emissions may be measured successively on applying the retarding potential to remove ions from the beam. The yield for the ions is obtained directly from the measured currents on subtracting out the neutral atom contribution. The ratio of the electron emissions for ion and neutral atoms when divided by the appropriate λ gives the ratio of γ_+ to γ_0. This with the knowledge of γ_+ gives the shown in figure 6 as a function of the particle kinetic energy. These data represent averages of some 5 or 6 values taken at different helium pressures and so different λ. Individual values deviated about.02 el/particle from the mean. The hot target readings were taken after flashing at 2200°K and reducing the temperature to about 1300°K. The cold target values were taken after flashing and then allowing the electron emission to reach a stable value. This required a rather long time for these pressures, i.e. the order of 30 seconds to reach one-half its maximum value on reducing the temperature from 1300°K. This was essentially independent of beam bombardment over the interval. The cold target measurements of γ are less reproducible than the hot target and show deviations as high as 10%.

The lower curves in figure 6 represent the electron yield from a hot target under helium ion and neutral atom bombardment for kinetic energies of 300 to 3500 ev. As would be expected, the neutral atom or kinetic ejection goes to zero with decreasing

energy. At 300 ev. the γ_c is actually too small to measure with any accuracy, $<$ .01el/particle. The ion yield would be expected to remain about constant with decreasing energy below 300 ev. The potential process yield is about .16 el/ion. This agrees with Hagstrom's value for He^+ on Mo covered with a monolayer of gas. Assuming that the kinetic yield for the ion is identical with the neutral atom yield, the results indicate that the potential yield remains almost constant to 2000 ev, and then decreases to about 0.09 electrons/particle at 3000 ev. The kinetic yield as is indicated by the neutral atom curve rises almost linearly with kinetic energy at first, leveling somewhat at 0.42 el/particle at 3000 ev. Since the beam is directed at 30° with the normal to the target, energies associated with the normal velocity are 0.75 of the beam energy. This would seem of little importance at small angles because of the roughness of the surface.

For a gas covered target which here will include several layers of gas, the yield is considerably increased for both ions and neutral atoms. At the low energy limit of the experiment, though, the difference in yield is about that for the hot target. Thus it is still equal to the low velocity potential yield. With increasing kinetic energy, this difference decreases until above 2500 ev, the neutral atom has the higher yield. These hot and cold target data were taken within a short time with the same helium pressure and so the same λ. Thus this peculiarity cannot be ascribed to an error in the determination of the neutral atom beam size.

Several suggestions may be advanced for the reason for this anomaly. 1) The presence of the adsorbed gas may hinder the operation of the potential mechanism with increasing ion velocity. 2) The kinetic yield for an ion is less than for a neutral atom at high velocities. It may be that the kinetic mechanism or a part of it can be ascribed to ionization by collision of the adsorbed gas atoms with the impinging helium atoms as well as ionization of the helium itself.[22] The subsequent neutralization of these ions would then, by a potential ejection process, produce the observed emitted electrons. If the ion approaching the surface were less proficient than the neutral atom in so ionizing the adsorbed gas, such an effect as the above could occur. For with increasing velocity the ion approaches closer to the surface before neutralization. At low velocities, this neutralization probably occurs before appreciable penetration of the adsorbed gas layers, while at higher velocities the ion may remain unneutralized through much of the adsorbed gas. A lower ionization cross-section for the ion would then result in a less rapid increase of the kinetic ejection with energy than occurs with the neutral atom. Little evidence on the relative ionization efficiencies of the ion and like neutral atom exist.[23] Rostagni found, for energies of less than 1 kev.,for helium in helium, the ions slightly more efficient and, neon in neon, the neutral atom more effective. No comparison seems available for unlike projectile and target atoms.

It is difficult to see, however, how such an ionization process could be sufficiently prolific to account for the high yield observed for a gas covered surface or even the yield of .42 el/part. for 3500 ev neutral atoms on a hot target. For if the potential yield is .16 el/part. or less, depending on the ion, several ionizations are obviously needed or a considerable contribution must come from the knock-on electrons of the ionizing collisions. However, there is evidence in velocity distributions for several processes and such ionization by collision may contribute a part of the yield. The release of electrons bound to electronegative adsorbed gases, as suggested by Walcher [10], could also account in part for the observed yields.

It should be noted in comparing the neutral atom yields for neutral atoms on a hot and a cold target that the increase is not constant throughout the velocity range. The ratio of yields decreases from about 8 at 500 ev to 2.3 at 3000 ev. The apparent threshold also decreases for the cold target.

ELECTRON VELOCITY DISTRIBUTIONS

1) Normal Velocity Distribution

In addition to a marked difference in γ for ions and neutral atoms, it would be expected that a difference in mechanisms would also produce unlike velocity distributions in the emitted electrons. The most common way of measuring the total velocity distribution is by use of the retarding field with a geometry approximating spherical symmetry. It is apparent that a geometry of definite symmetry is needed in order that a known velocity component be under examination. In the experiments contemplated here, the reflected neutral atoms will produce an electron emission from a collector. Since this collector is gas covered, the reflected particles, even though reduced in energy, will produce an electron emission comparable and, in some cases, larger than the electron emission from the hot target. Mott-Smith and Langmuir[24] have derived the equations for the current received by a collector with either an inner or an outer emitter assuming a maxwellian initial velocity distribution for the common symmetrical arrangements - plane-parallel, cylindrical, and spherical. These calculations show the difficulty of saturating the current from an external emitter with any concavity. True saturation is theoretically impossible but Langmuir shows that practical saturation occurs with relatively high collecting voltages. For example, an external emitter of 1 cm. radius at a temperature of 1000°K and an internal collector of 1 mm. radius would require 26 volts for effective saturation. This is for electrons with an average energy of a few tenths of an electron volts. Greater difficulty in attaining

saturation would occur with the more energetic electrons emitted by ions on neutral atoms.

To examine the velocity distribution of one or both sets of electrons when emission will occur from either electrode requires that while one group is under a retarding field the other group be saturated. If this is not so, an unknown contribution to the currents passing from the emitter to the collector is introduced by an increasing saturation of the electron current from the collector. Such a contribution might conceivably, depending on the current sizes, completely alter the true retarding potential-current characteristic of the target emission.

Since any concavity of the collector will contribute to this difficulty of saturation of the back current, it was decided to use parallel planes as emitter and collector. The use of finite parallel planes will alleviate the difficulty but will permit the escape of some electrons at the edge. The apparatus for this part has been described above. For the measurements of the normal velocity distribution, the Faraday cage collector is connected to the collector plane. The target used here was directly heated and for most of the experiment by a half-wave rectified current. The voltage drop across the exposed face of the heated ribbon was less than 0.2 volts. To determine the effect of this heating current, a no field angular distribution measurement was made for thermionic electrons emitted by the target with and without a half-wave pulsing voltage applied to hold the electrons during the half cycle of heating. For these measurements the target was biased relative to the brass plates

+ 0.2 volts determined by the customary semi-log plot of current vs. retarding voltage using pulsed emission. The slit of the Faraday cage collector was 0.05 x 1.0 cm with the long dimension parallel to the target. The current observed as a function of the slit position in mm. from the normal to the center of the target is shown in figure 7. The difference between the two curves is not sufficiently marked so that the heating current would be expected to cause noticeable difficulty for the 10 - 20 times more energetic electrons removed by ion or neutral atom bombardment. Consequently, the measurements on the normal velocity distribution were made without the pulsing which was found to effect adversely the performance of the D.C. amplifiers used.

A typical current vs. potential difference curve is shown in figure 8. On the right hand side I_T would represent the target electron emission with the applied retarding potential difference on the abscissa. For an initial maxwellian velocity distribution and with plane-parallel geometry the logarithm of this current is linear with the retarding voltage. In many cases[1,8], this has been found true for electrons removed by neutral and metastable atoms. Probably this similarity with the thermionic emission arises from the fact that what is measured here is a current representing an integration with a varying lower limit over the velocity distribution. As a rapidly varying function of this type it appears to reduce to a linear semilogarithmic function. In any case, in order to observe any gross differences between the velocity distributions and not with the anticipation of a maxwellian distribution, the

measurements have been reduced to the semi-logarithmic plots shown in figure 9. The electron currents have not been reduced to unit incident particle and further to reduce the confusion in the graph, the curves have been arbitrarily displaced along the ordinate. All curves labelled ions include an emission arising from neutral atoms which is 10 - 15% of the whole. This results from the convenience of taking the initial data with a mixed beam and then neutral atoms alone. The contribution of the neutral atoms may be readily subtracted out, but from the similarity of the two curves and the small neutral atom contribution, this seemed unnecessary.

Within the experimental error, all the curves, except 2000 ev, seem to be reducible to two straight lines in the semi-log plot. For the ions on the hot target there is only a slight change in slope between the two plots. For the neutral atoms on a hot target, the change in slope is more evident but is still slight. While for the cold target, the change in slope is quite marked. Thus it would seem that there are two groups of electrons. The high energy group corresponding to the lower slope, right hand section is present for all three cases. The lower energy group is only slightly evident for the ions, more so for the neutral atoms on a hot target and for the cold target it is the major source of electrons. A slight change occurs in the slope of that portion of the curves corresponding to the more energetic electrons with particle energy for hot or cold targets. This portion becomes a little less steep with increasing energy. The low energy portions exhibit similar slopes for like conditions, although the break

point shifts corresponding to different relative numbers of electrons in the two groups. The slope of the curves are of the order of those observed by Greene and others[8]; that is, they correspond to temperatures of 16,000 to 40,000°K.

The similarity of the ion and neutral atom plots would indicate like mechanisms for at least a part of the emission. This is true, also, for a gas covered surface but the relative contribution of this high energy group of electrons is much smaller. A second process which is more evident with increasing gas adsorption* produces a low energy group and is responsible for much of the greater yield from the gas covered surface. The energy of the incident neutral atom affects primarily the total number of emitted electrons and does not alter appreciably the normal velocity distribution.

Ionization by collision of the adsorbed gas atoms as well as the incident helium atom could account for both the above conclusions. Since the adsorbed gas will have a lower ionization energy, the electrons emitted on neutralization will be less energetic than for the helium ion. Walcher's[10] proposal of released electrons from adsorbed negative ions would also account for the increasing prominence of the low energy group with adsorption of gas.

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* It should be realized that the first partial layer of chemisorbed oxygen present on the hot target is highly bound to the surface atoms and is immobile.[21] The additional adsorbed gas is much less tightly bound, with the molecules capable of considerable surface mobility as well as an oscillatory motion normal to the surface.[25] Thus gas adsorption may introduce unlike changes in the electron emission depending on the character of the adsorption.

2) Tangential Component Velocity Distribution

The distribution in a component of the tangential velocity may be measured directly by applying an accelerating potential difference between the plates and by observing the current to the slit collector as a function of slit position.[26] If we denote by z the direction normal to the target, x the direction of motion of the slit, and y at right angles to these, then the electron current received by the slit collector at any position x is proportional to

$$\int_0^\infty v_z f_1(v_z)\,dv_z \int_{v_y'}^{v_y''} f_2(v_y)\,dv_y \int_{v_x'}^{v_x''} f_3(v_x)\,dv_x$$

where $v_z\, f_1(v_z)\, f_2(v_y)\, f_3(v_x)$ = initial velocity distribution in the flux normal to the target surface.

v_x' = initial x-component velocity to just reach the inner edge of the collector slit

$$v_x' = \frac{1}{2} v_z \left(\frac{x - \delta/2}{z_1}\right)\left(1 + \left(1 + \frac{Ve}{\frac{1}{2} m v_z^2}\right)^{1/2}\right)$$

$$v_x'' = \frac{1}{2} v_z \left(\frac{x + \delta/2}{z_1}\right)\left(1 + \left(1 + \frac{Ve}{\frac{1}{2} m v_z^2}\right)^{1/2}\right)$$

v_y', v_y'' = similar expressions but independent of x corresponding to the top and bottom of the slit.

In the above

V = applied potential difference

δ = slit width along x

z_1 = separation of the plates

If we can assume $Ve/\frac{1}{2}mv_z^2 >> 1$, the limits in the integrations reduce to ones in which v_z does not appear. Thus the first two integrals are definite and are not functions of x. Only the third remains so and approximating the integral over the narrow slit by a differential expression, we have that the collector current is proportional to

$$f(v_x) = \frac{2}{2}\sqrt{\frac{2Ve}{mv_x^2}}\Big) \sqrt{\frac{Ve}{2mv_x^2}} \Delta x$$

This method has the advantage in that it gives directly the velocity distribution, and can be quite sensitive to small contributions.

Reasonable resolution in the distribution is attained with a potential difference V of about 100 v. To check the validity of the above assumption, measurements may be made at several values of V and then compared. It is evident, that for the most energetic electrons possible under helium ion bombardment, the assumption is not valid. But for the much lower average energy it should be reasonably good. Electrons in a given group of width Δv_x at v_x are received by the collector in Δx at x where these are related by the square root of the potential difference. Thus all measurements may be reduced to the same abscissa $x/\sqrt{V}$. The ordinates may be corrected by simply matching at x =o. Figure 10 shows such sets of measurements for 1000 ev helium ions on W with accelerating potential differences of 48 and 106 volts. For lower accelerating potential differences, the effect of the component of the initial velocity of the electrons was apparent in narrowing the distribution. The agreement within experimental error of the 48 and 106 volt distributions justifys

the assumption. For all other reported measurements the potential difference was 106 v. A 10 v p.d. between slit/ and collector (slit negative) was applied to hold electrons released by particles reflected from the target. The lower scale on the abscissa gives the x-component of the initial velocity of the electrons collected in units of (electron volts)$^{1/2}$.

In all measurements the high velocity tail of the distribution, shown enlarged in figure 10, was found. It was thought that this might be a background electron current produced by the reflected particles bombarding the slit edges. If this were so, though, the current would be primarily a function of slit position and not applied potential difference, and consequently data observed at different V would not coincide on reduction to a common abscissa. Further, when an axial magnetic field was present to keep electrons emitted from the target from the collector, the current observed at large χ reduced to zero. It, therefore, seems that the tail of the curve actually represents electrons of high tangential velocity from the target.

Figure 11 shows the tangential x-component velocity distribution for 1000 ev helium ions and ne utral atoms on a hot target and neutral atoms on a cold target. The ordinate is the current received by the collector at χ weighted in the case of each curve so that the area under the curve is proportional to the electron yield, that is, to γ. When the curves are compared by matching at $\chi = 0$, the distributions are not much different except at the high energy end. The neutral atoms on the hot target always showed

relatively fewer electrons in the intermediate range and more at the high velocities than did the ions. For the cold target, the relative number of fast electrons decreases although the total emission is greater. This relative change in electron distribution on gas adsorption is shown better in the insert in figure 11. Here the ratio for hot and cold targets of the number of electrons of a given velocity range per unit beam size are compared. Most of the increased emission occurs for low energy electrons with a rather sharp delineation between high and low energy groups. The coincidence of the high velocity end of the ion and the cold target neutral atom distributions is just chance. The cold yield as noted before is dependent by 10% on the target treatment.

In figure 12, the tangential velocity distributions for four different neutral atom energies are compared. The ordinate is again adjusted so that the areas under the curves are proportional to the electron yields. When compared by matching at χ = o, the low particle energy curves show relatively more fast electrons. When plotted as in figure 12, the number of fast electrons increases about linearly with the energy of the neutral atom.

The tangential velocity distributions are in general accord with the normal velocity measurements with the same type of change occurring on gas adsorption. The process in which the fast electrons originate (if this is not a spurious effect) must be a kinetic one which does not involve an ionization energy in a direct or secondary process. The maximum energy for an electron ejected by the one-stage

process by an ion is $I - 2\phi$ (see figure 1b). For helium ions on tungsten this is about 15 ev, and less for adsorbed gas ions. The results indicate that the yield of the fast electrons is primarily dependent on the kinetic energy of the bombarding particle, and not so much on its ion character or the adsorbed gas status. Thus, these electrons would not seem to be released electrons from electronegative adsorbed atoms or knock-on electrons from ionizing collisions. The low velocity electrons (velocities less than $4\ (\text{ev})^{1/2}$) liberated under neutral atom impact could well be produced by ionization by collision of the adsorbed gas and the incident atom and subsequent neutralization.

ANGULAR DISTRIBUTION OF REFLECTED PARTICLES

Since the reflected particles are sufficiently energetic to liberate electrons, it is possible to obtain an angular distribution measure weighted by the electron yield. The present apparatus is not ideal for this measurement because of the rapid decrease of the effective area of the slit with increasing angle with the normal to the target. Figure 13 shows such a distribution for particles reflected from a hot and a cold target under 1000 ev ion bombardment. It seems likely that the maximum in the neighborhood of the specular reflection angle results from a greater energy of reflection for these particles.

APPENDIX

Calculation of the ratio λ = the electron current removed from the collector under ion bombardment of the target to that under neutral bombardment.

If the ion current entering the neutralizing regions is I, the ion current remaining after traversing the region is

$$i_+ = I e^{-k\sigma}$$

where k = constant depending on the helium gas pressure, length of neutralizing path, etc.

σ = cross-section for neutralization

The neutral atom "current" produced is

$$i_0 = I\left(1 - e^{-k\sigma}\right)$$

$$\lambda = \frac{i_+}{i_0} = e^{-k\sigma} / 1 - e^{-k\sigma} \quad ; \quad 1/\lambda = e^{k\sigma} - 1$$

For an ion beam of different energy

$$1/\lambda' = e^{k\sigma'} - 1$$

Combining these to eliminate k, we have

$$\lambda' = \frac{1}{\left(\frac{1+\lambda}{\lambda}\right)^{\alpha} - 1}$$

where $\alpha = \frac{\sigma'}{\sigma}$

For a chosen value of λ, λ' may be evaluated as a function of the energy of the ion beam. The values used in figure 4 are tabulated below.

TABLE I

λ_{1000} = experimental value = 1.85

V	σ (Jackson)[14] (units πr_0^2)	σ (MS DB)[12,13] (πa_0^2)	λ' (Jack.)	λ' (MS DB)
500	8.64	9.2	1.67	1.53
1000	7.94	7.9	1.85	1.85
1500	7.53	7.1	1.97	2.12
2000	7.23	6.5	2.08	2.35
2500	7.00	6.1	2.16	2.54
3000	6.82	5.7	2.23	2.75
3500	6.66	5.4	2.29	2.92
4000	6.52	5.2	2.35	3.05

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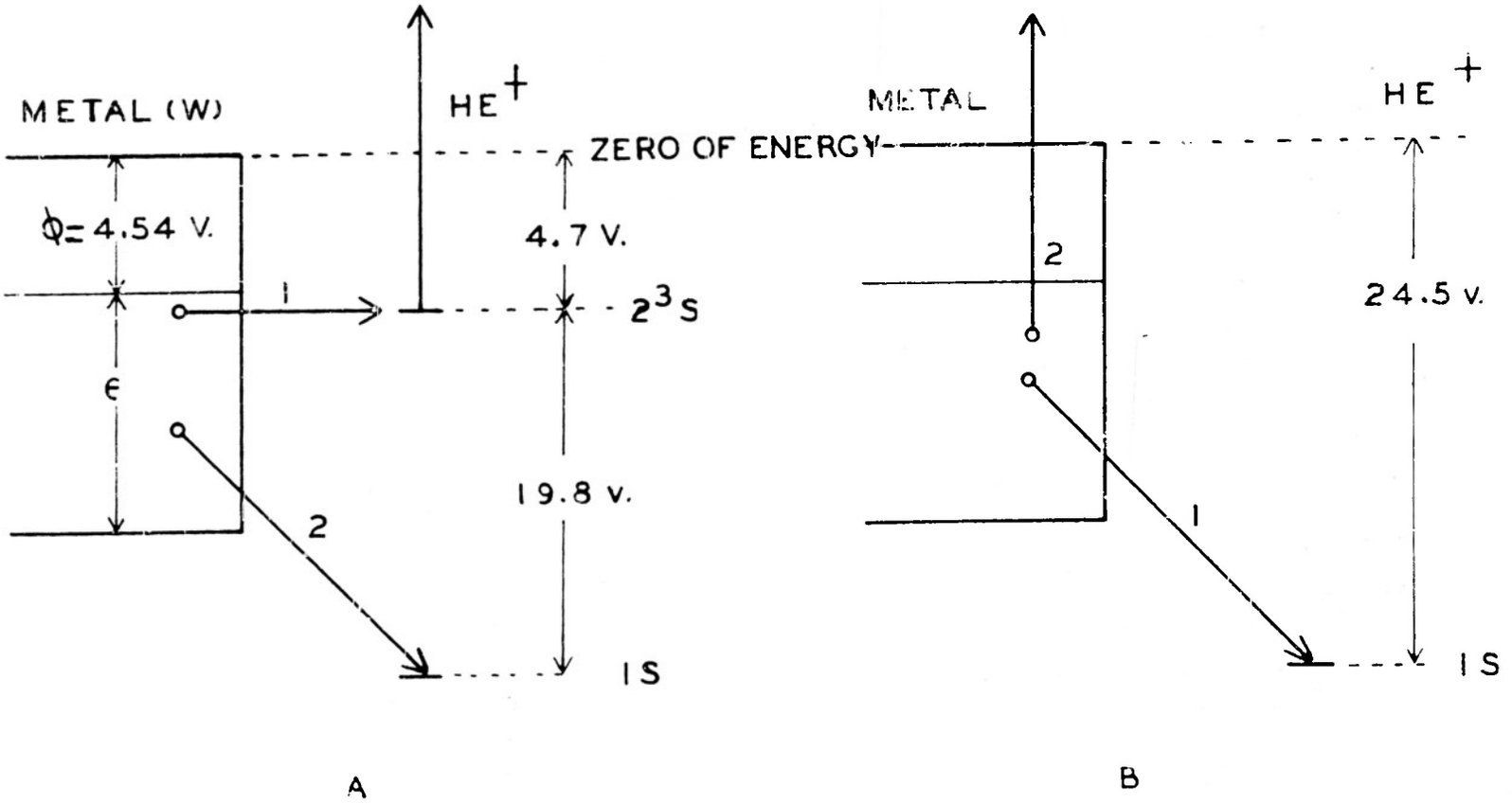
METAL (W)
HE+
ZERO OF ENERGY
Φ= 4.54 V.
4.7 V.
1
2³S
ϵ
19.8 v.
2
1S
A
METAL
HE+
2
24.5 v.
1
1S
B

FIG. 1

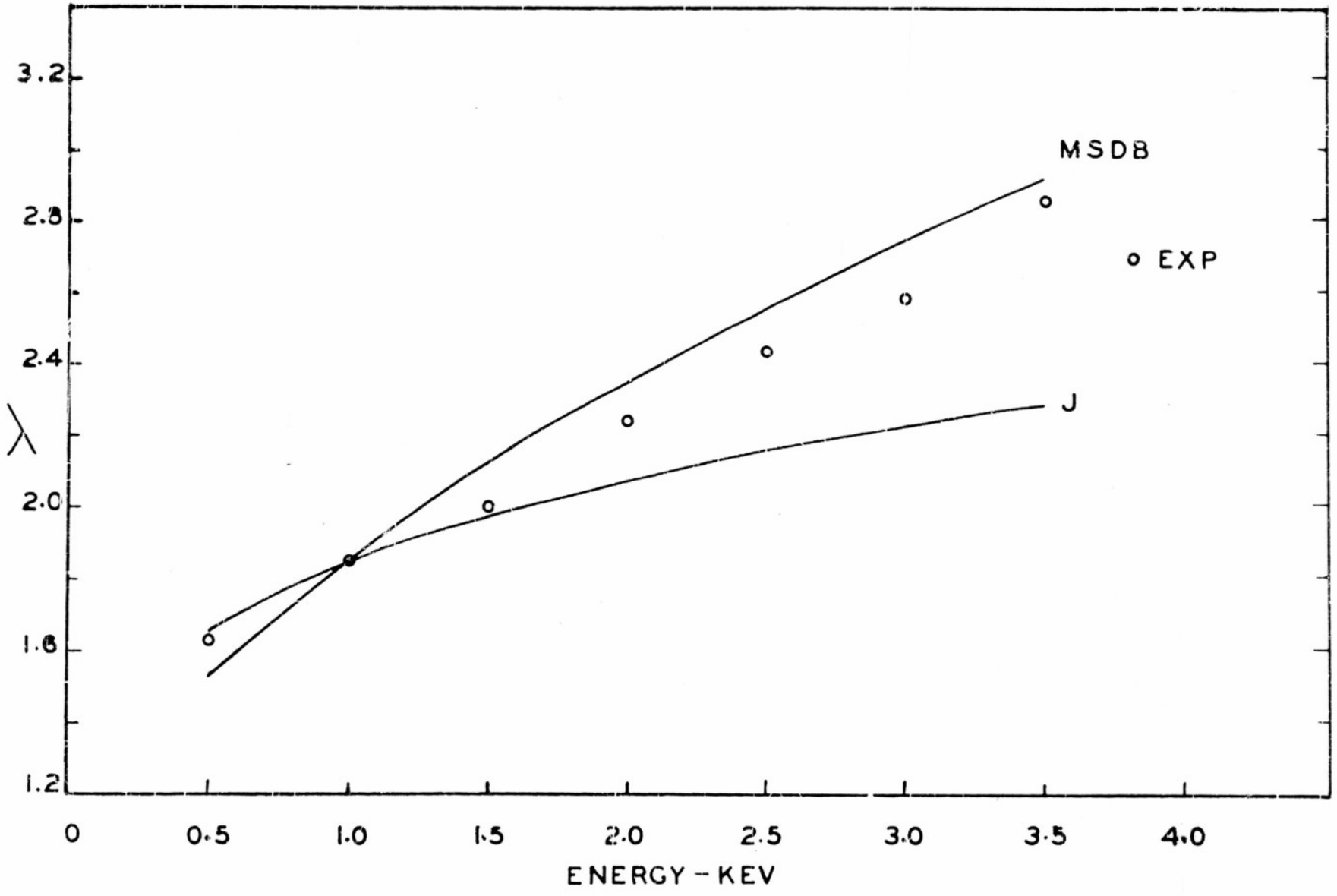

FIG. 4

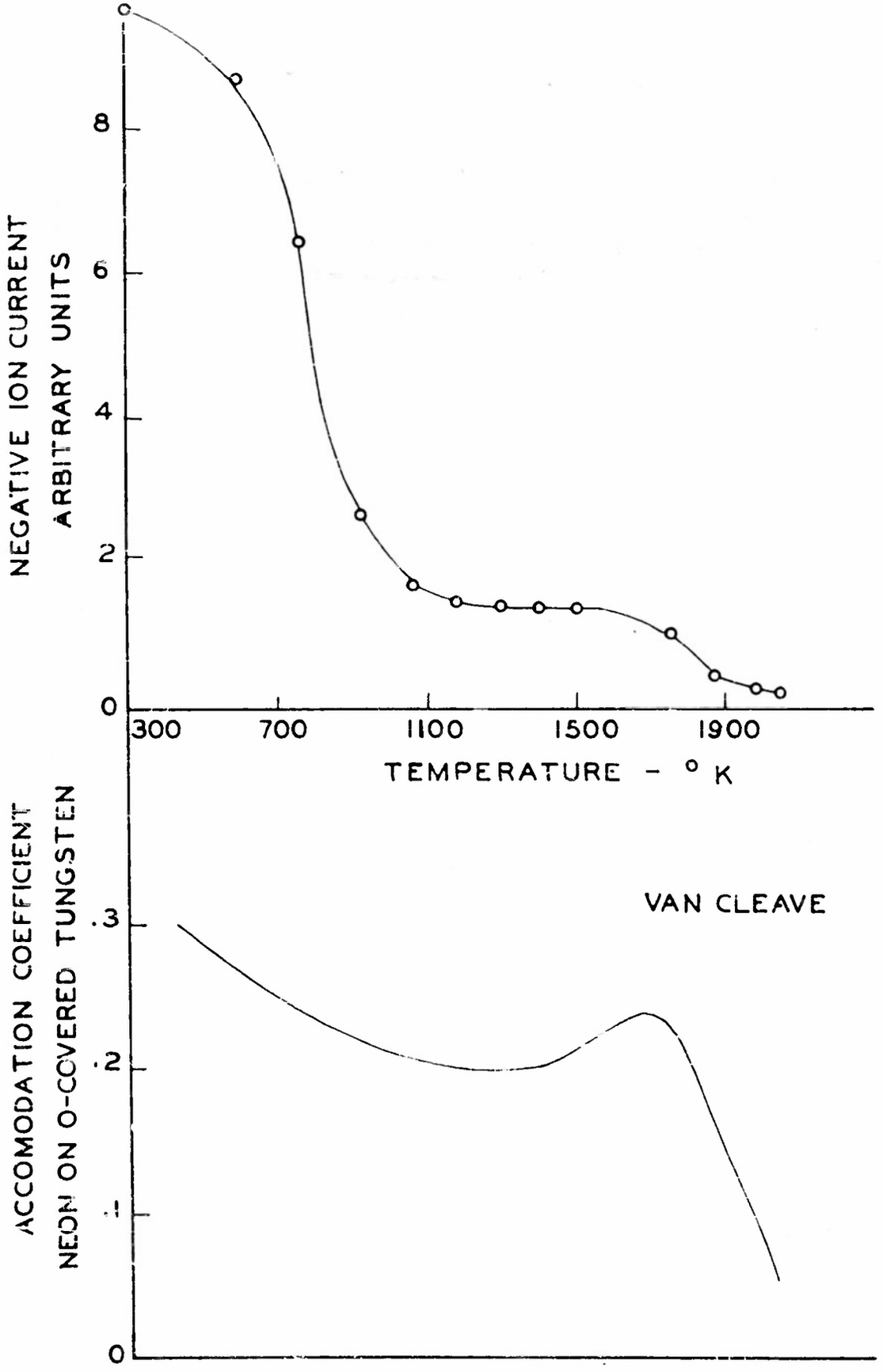
NEGATIVE ION CURRENT
ARBITRARY UNITS
8
6
4
2
0
300
700
1100
1500
1900
TEMPERATURE - ° K
ACCOMODATION COEFFICIENT
NEON ON O-COVERED TUNGSTEN
VAN CLEAVE
.3
.2
.1
0

FIG. 5

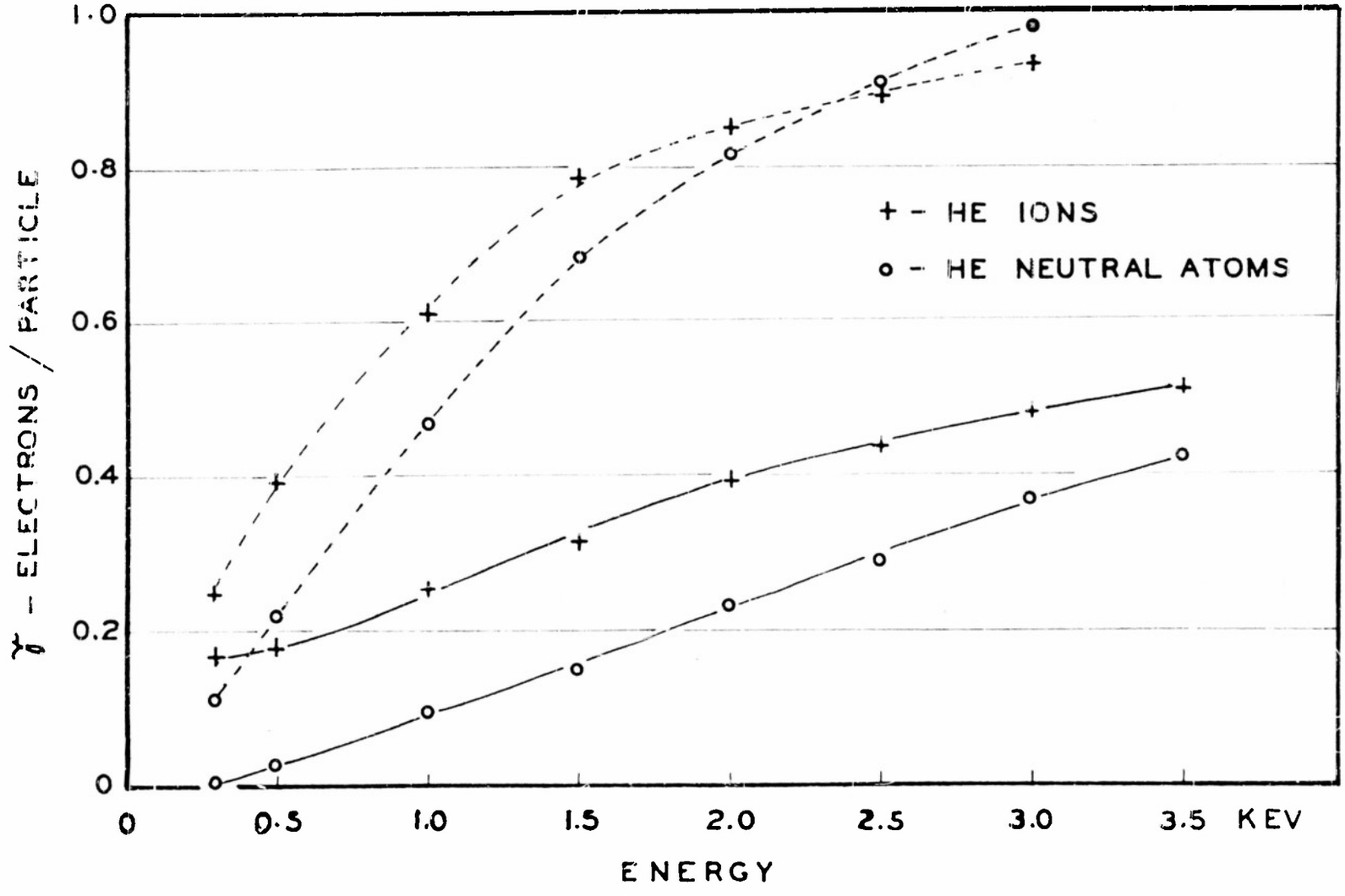
1.0
0.8
0.6
0.4
0.2
0
γ_θ - ELECTRONS / PARTICLE
+ - HE IONS
o - HE NEUTRAL ATOMS
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5 KEV
ENERGY

FIG. 6

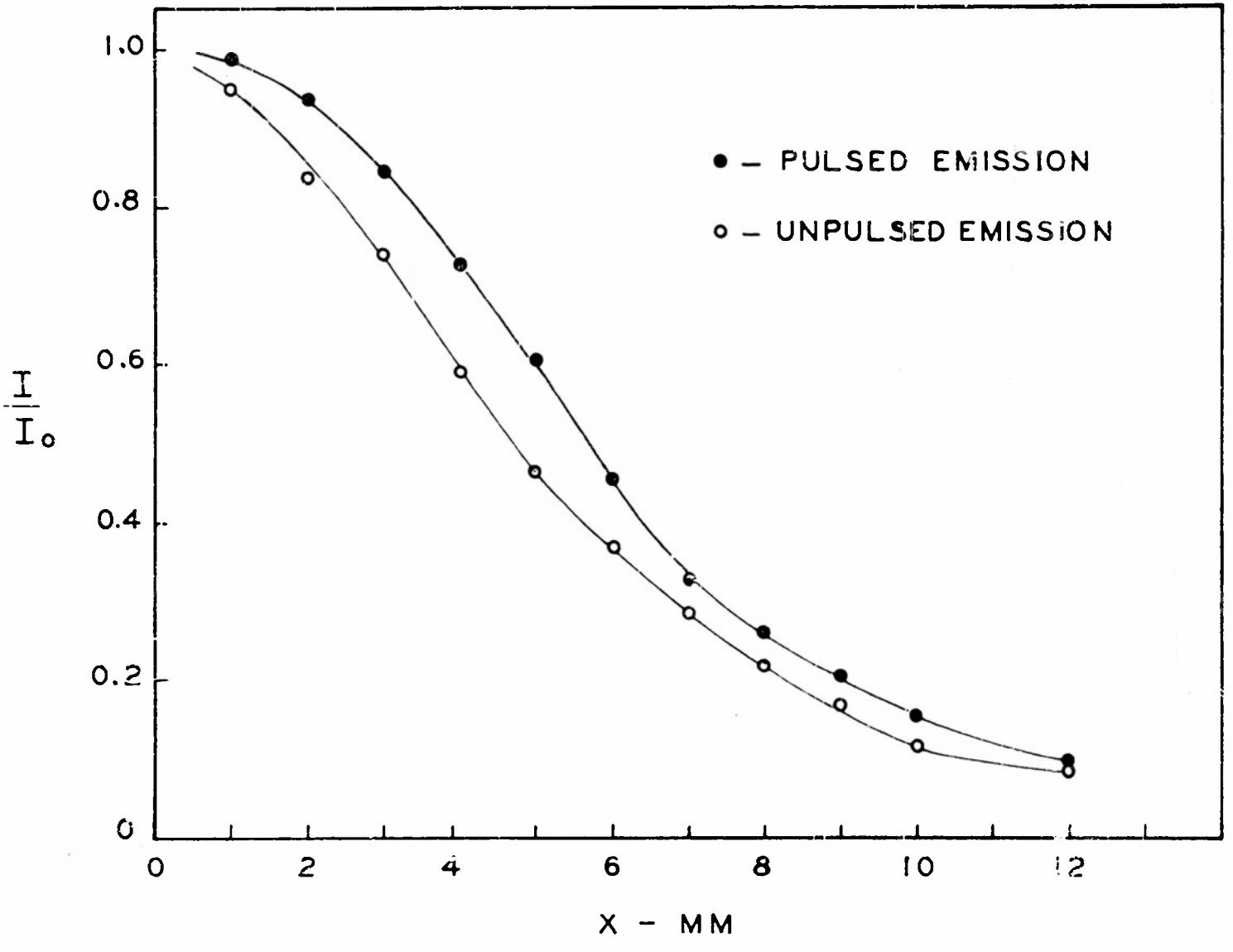
1.0
0.8
0.6
0.4
0.2
0
I/I₀
● – PULSED EMISSION
○ – UNPULSED EMISSION
0
2
4
6
8
10
12
X – MM

FIG. 7

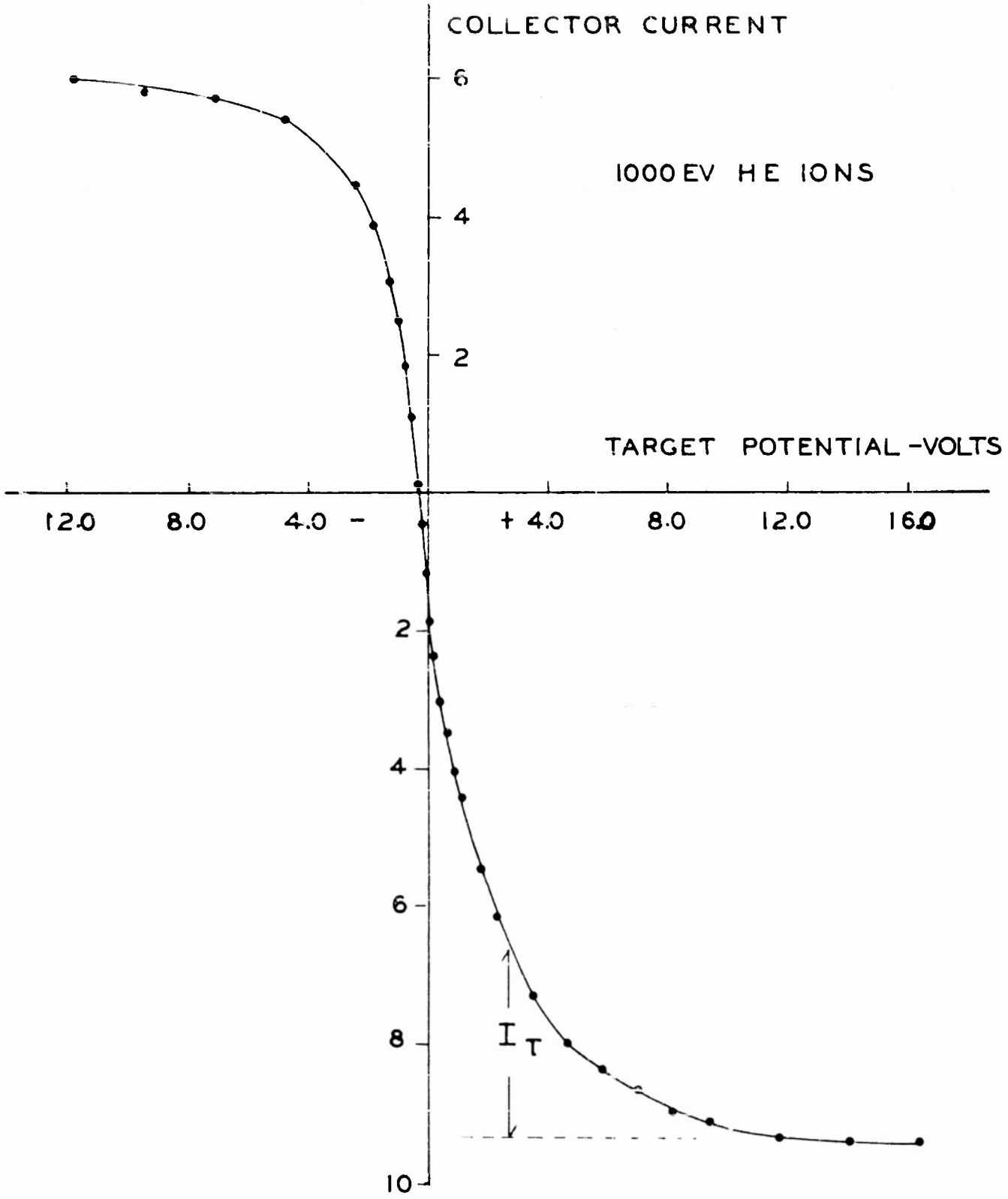
COLLECTOR CURRENT
6
4
2
1000 EV HE IONS
TARGET POTENTIAL -VOLTS
12.0
8.0
4.0
-
+ 4.0
8.0
12.0
16.0
2
4
6
8
10
I_T

FIG. 8

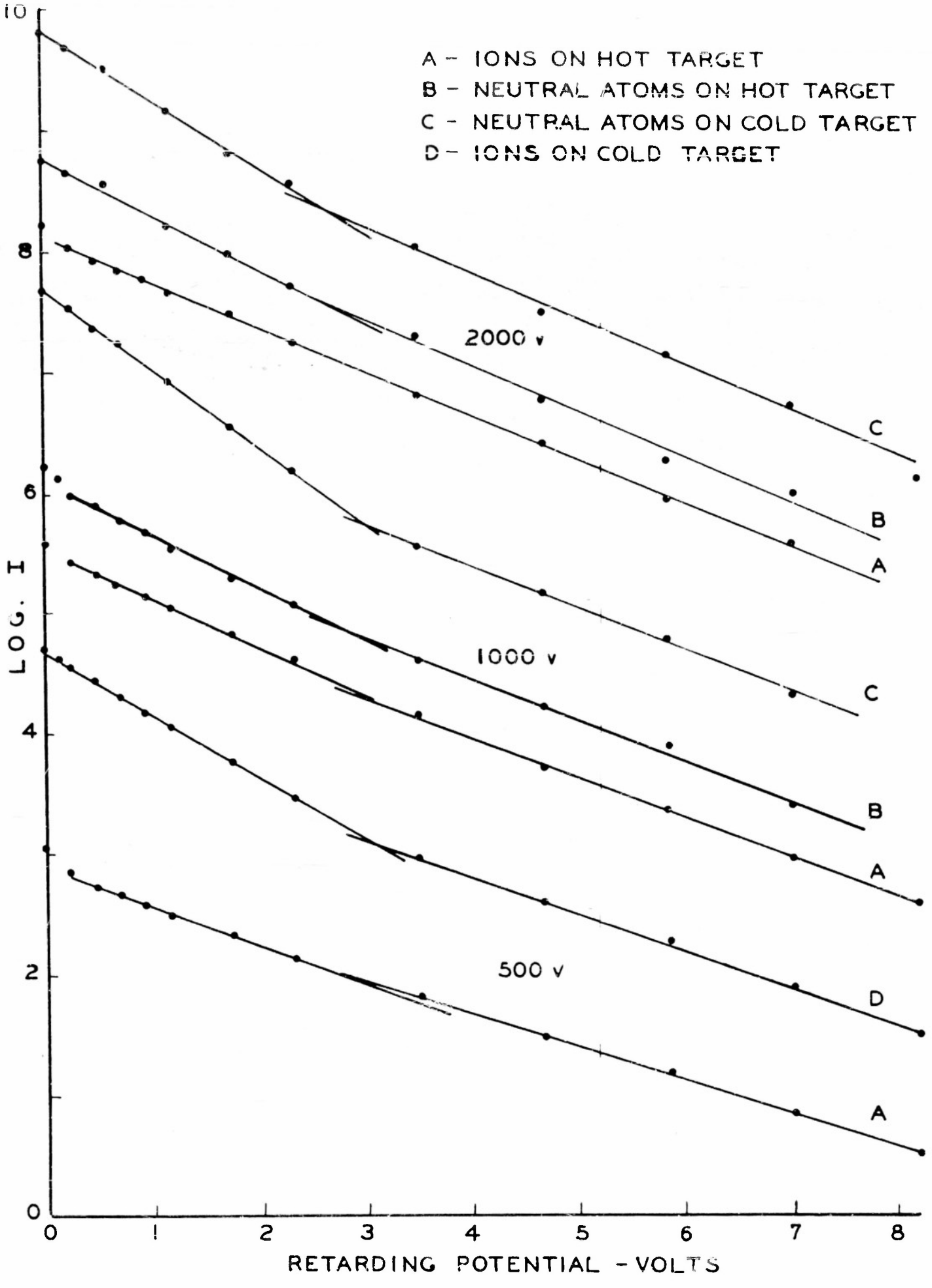
A – IONS ON HOT TARGET
B – NEUTRAL ATOMS ON HOT TARGET
C – NEUTRAL ATOMS ON COLD TARGET
D – IONS ON COLD TARGET
2000 v
1000 v
500 v
C
B
A
C
B
A
D
A
LOG. I
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
RETARDING POTENTIAL – VOLTS

FIG. 9

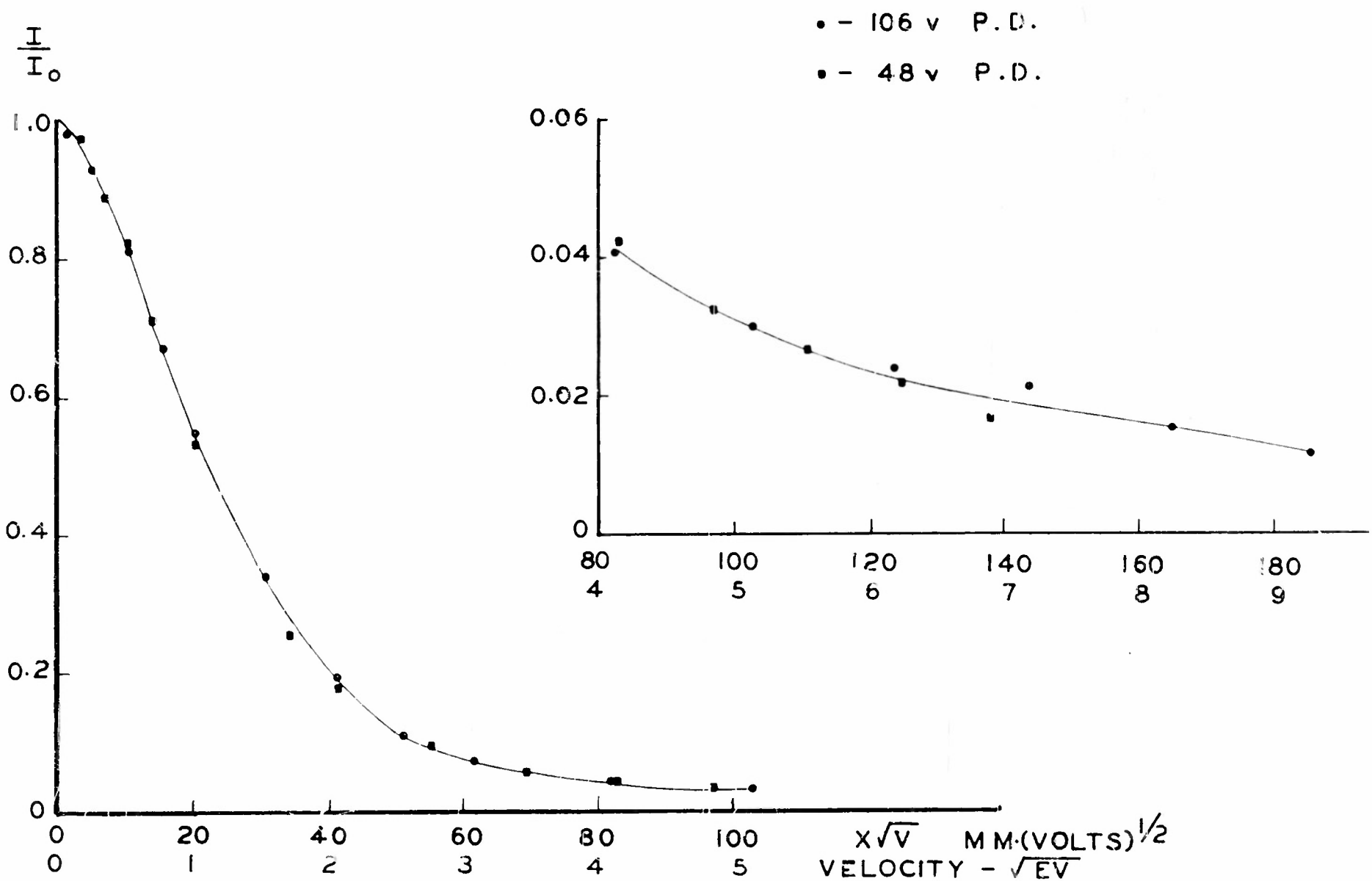
• - 106 v P.D.
• - 48 v P.D.
I/I0
1.0
0.8
0.6
0.4
0.2
0
0.06
0.04
0.02
0
0
20
40
60
80
100
0
1
2
3
4
5
80
100
120
140
160
180
4
5
6
7
8
9
X√V MM·(VOLTS)1/2
VELOCITY - √EV

FIG. 10

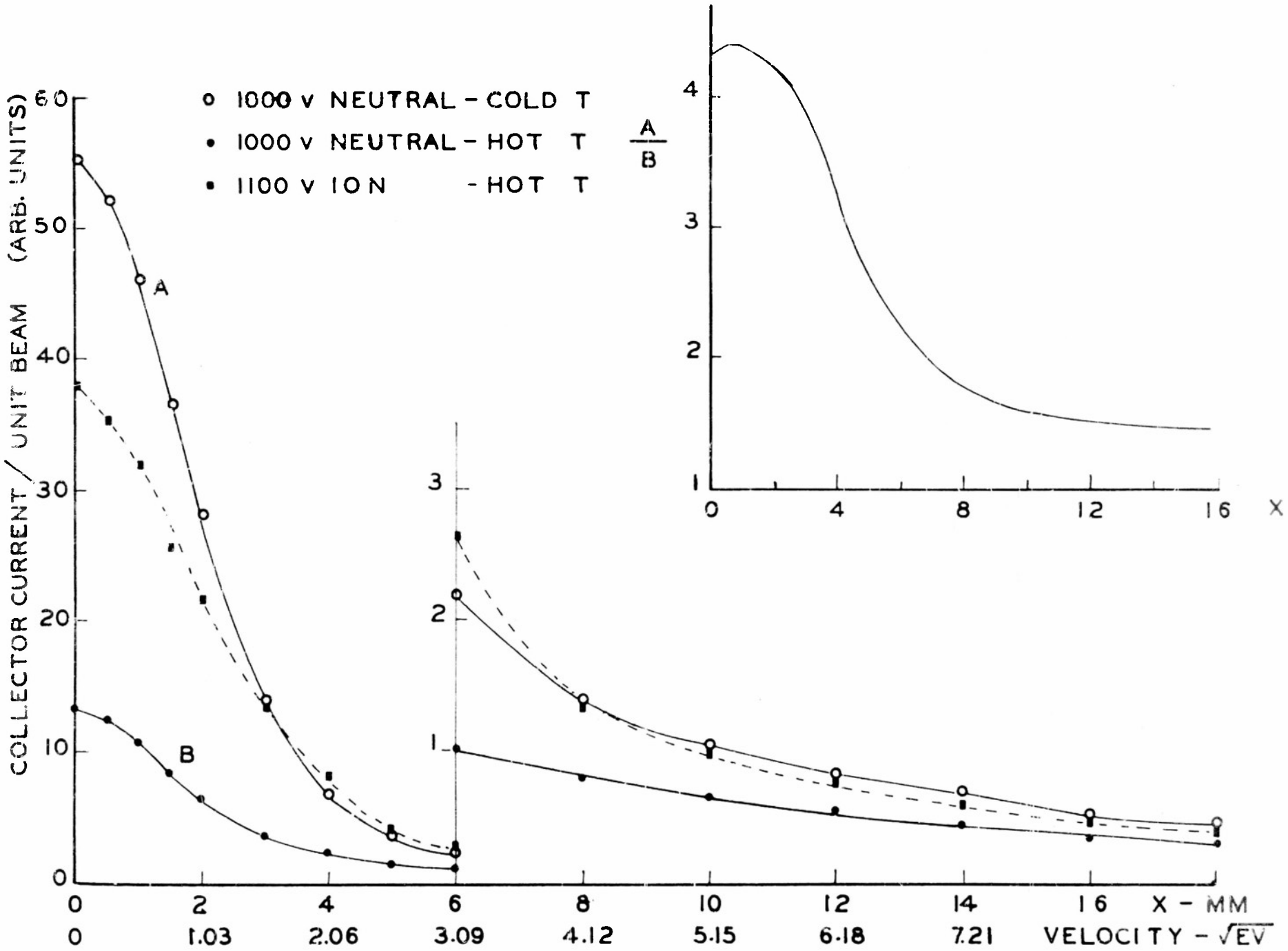
o 1000 v NEUTRAL - COLD T
• 1000 v NEUTRAL - HOT T
▪ 1100 v ION - HOT T
A/B
COLLECTOR CURRENT / UNIT BEAM (ARB. UNITS)
A
B
X - MM
VELOCITY - √EV
0
2
4
6
8
10
12
14
16
1.03
2.06
3.09
4.12
5.15
6.18
7.21
10
20
30
40
50
60
1
2
3
X

FIG. 11

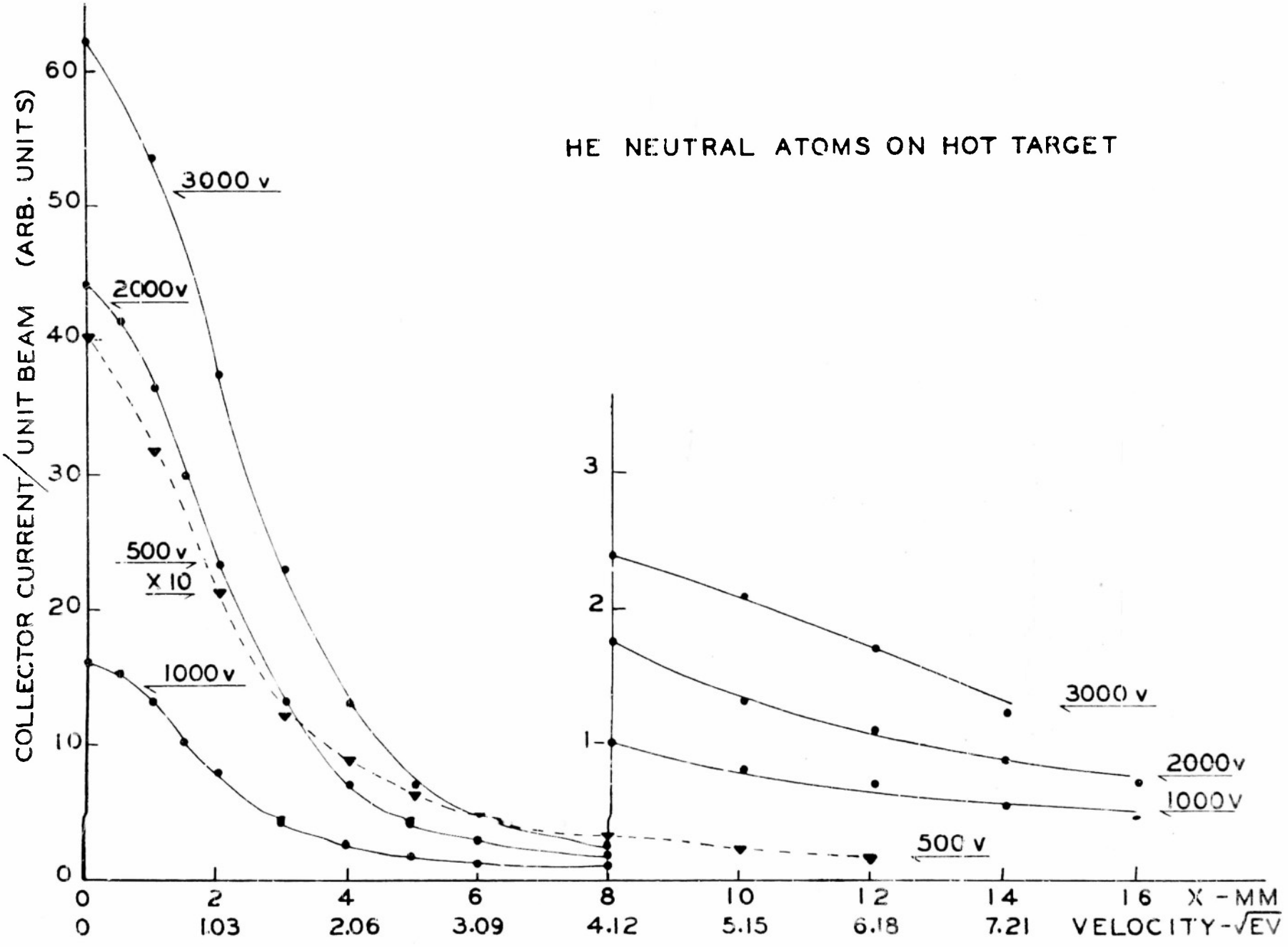
HE NEUTRAL ATOMS ON HOT TARGET
COLLECTOR CURRENT/UNIT BEAM (ARB. UNITS)
3000 v
2000v
500 v
X 10
1000v
500 v
X - MM
VELOCITY - √EV

FIG. 12

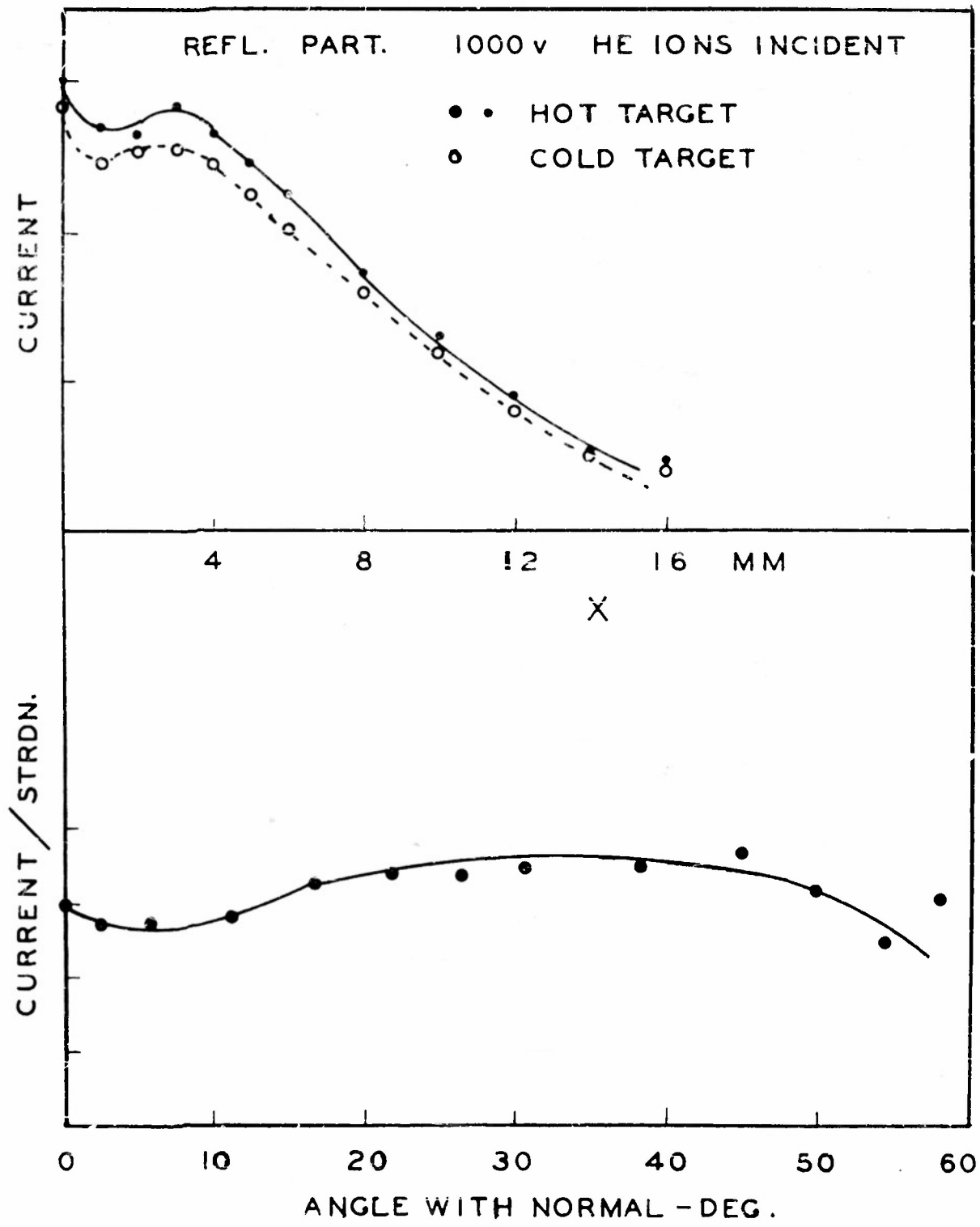
REFL. PART. 1000 v HE IONS INCIDENT
HOT TARGET
COLD TARGET
CURRENT
4
8
12
16 MM
X
CURRENT / STRDN.
0
10
20
30
40
50
60
ANGLE WITH NORMAL - DEG.

FIG. 13